Quarkonia
in Deconfined Matter

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Quarkonium Production in Elementary and Heavy Ion Collisions

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The Island of the Day before

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Roberto aveva deciso di concedere solo la metá del proprio spirito alle cose in cui credeva (o credeva di credere),

per tener l'altra disponibile nel caso che fosso vero il contrario.

Roberto had decided to reserve only half of his mind for the things which he believed (or believed to believe),

so that he would have the other half free in case the opposite should turn out to be true.

Contents

1. Quarkonia are very unusual hadrons

heavy quark ($Q\bar{Q}$) bound states stable under strong decay

- heavy: $m_c \simeq 1.2 - 1.4$ GeV, $m_b \simeq 4.6 - 4.9$ GeV
- stable: $M_{c\bar{c}} \leq 2M_D$ and $M_{b\bar{b}} \leq 2M_B$

What is "usual"?

- light quark ($q\bar{q}$) constituents
- hadronic size $\Lambda_{\rm QCD}^{-1} \simeq 1$ fm, independent of mass
- loosely bound, $M_\rho - 2M_\pi \gg 0,\ M_\phi - 2M_K \simeq 0$
- relative production abundances $\sim$ energy independent, statistical: at large $\sqrt{s}$, rate $R_{i/j} \sim$ phase space at T_c
- $(dN_{\rm ch}/dy) \sim \ln s$

Quarkonia: heavy quarks $\Rightarrow$ non-relativistic potential theory

Jacobs et al. 1986

Schrödinger equation $\left\{2m_c - \frac{1}{m_c}\nabla^2 + V(r)\right\}\Phi_i(r) = M_i\Phi_i(r)$

with confining ("Cornell") potential $V(r) = \sigma\, r - \frac{\alpha}{r}$

state	J/ψ	χ_c	ψ'	Υ	χ_b	Υ'	χ_b'	Υ''
mass [GeV]	3.10	3.53	3.68	9.46	9.99	10.02	10.26	10.36
ΔE [GeV]	0.64	0.20	0.05	1.10	0.67	0.54	0.31	0.20
ΔM [GeV]	0.02	-0.03	0.03	0.06	-0.06	-0.06	-0.08	-0.07
radius [fm]	0.25	0.36	0.45	0.14	0.22	0.28	0.34	0.39

($m_c = 1.25$ GeV, $m_b = 4.65$ GeV, $\sqrt{\sigma} = 0.445$ GeV, $\alpha = \pi/12$)

excellent account of full quarkonium spectroscopy:

spin-averaged masses , binding energies, radii.

masses to better than 1 %...

NB:

recent work on field theoretical quarkonium studies,

NRQCD — Brambilla & Vairo 1999, Brambilla et al. 2000

$\Rightarrow$ quarkonia are unusual

– very small, mass-dependent size:

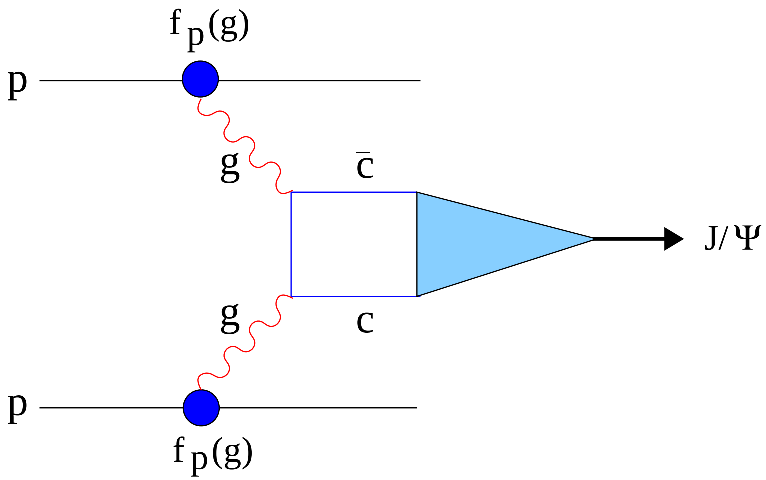
$$r_{J/\psi} \simeq 0.25 \text{ fm}, \; r_{\Upsilon} \simeq 0.14 \text{ fm} \quad \ll \Lambda_{\rm QCD}^{-1} \simeq 1 \text{ fm}$$

– very tightly bound:

$$\left.\begin{array}{l} 2M_D - M_{J/\psi} \simeq 0.64 \text{ GeV} \\ 2M_B - M_{\Upsilon} \quad \simeq 1.10 \text{ GeV} \end{array}\right. \gg \Lambda_{\rm QCD} \simeq 0.2 \text{ GeV}$$

primary production via partonic interaction dynamics

Einhorn & Ellis 1975, Baier & Rückl 1983, Lansberg 2006



given parton distribution functions from DIS,
$c\bar{c}$ production is perturbatively calculable (cum grano salis)

J/ψ binding is not, but it is independent of collision energy:

$$R[(J/\psi)/c\bar{c}] \sim |\phi_{J/\psi}(0)|^2 \neq f(s)$$

results for/from elementary collisions:

- $(dN_{c\bar{c}}/dy) \sim s^a$
- $(dN_{\mathrm{ch}}/dy) \sim \ln s$
- $N_{c\bar{c}}/N_{\mathrm{ch}}$ grows with collision energy compare $[N_{s\bar{s}}/N_{\mathrm{ch}}]$

$\Rightarrow$ heavy flavor production is dynamical and not statistical

- $(dN_{J/\psi}/dy)/(dN_{c\bar{c}}/dy) \simeq 0.02$, compare $[N_\rho/N_{\mathrm{ch}}]$
  factor 10 bigger than ratio of statistical weights at T_c
  much more hidden charm than statistically predicted
- $(dN_{\psi'}/dy)/dN_{J/\psi}/dy) \simeq 0.2$, compare $[N_\rho/N_\omega]$
  factor five bigger than ratio of statistical weights at T_c
  ratios of states $\sim$ wave functions, not Boltzmann factors

$\Rightarrow$ quarkonium binding is dynamical and not statistical

Quarkonium production in elementary collisions: no medium

What happens to quarkonia in hot strongly interacting media?

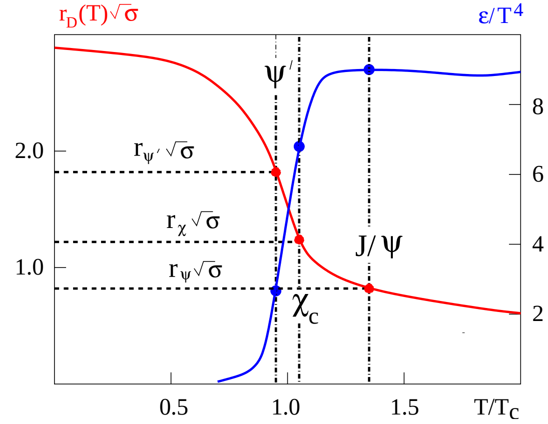
2. Quarkonia melt in a hot QGP

Matsui & HS 1986, Karsch et al. 1988

- **QGP consists of deconfined color charges, hence**
  $\exists$ color screening for $Q\bar{Q}$ state
- **screening radius $r_D(T)$ decreases with temperature T**
- **if $r_D(T)$ falls below binding radius r_i of $Q\bar{Q}$ state i,**
  Q and $\bar{Q}$ cannot bind, quarkonium i cannot exist
- **quarkonium dissociation points T_i, from $r_D(T_i) = r_i$,**
  specify temperature of QGP

Color screening $\Rightarrow$ binding weaker and of shorter range

when force range/screening radius become less than binding radius, Q and $\bar{Q}$ cannot "see" each other



$\Rightarrow$ quarkonium dissociation points

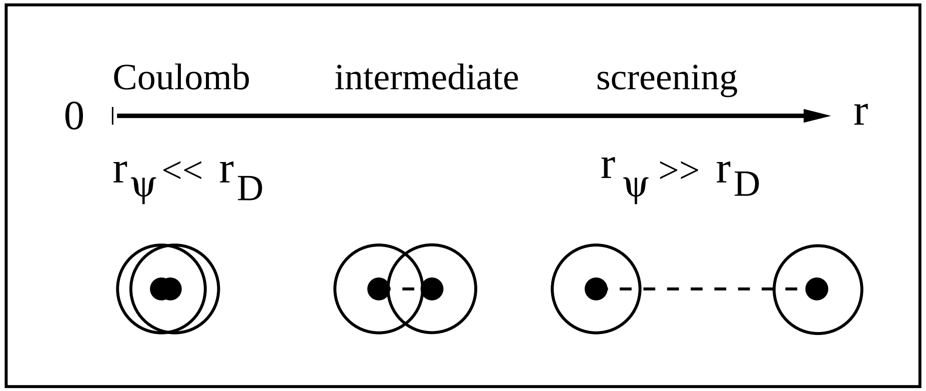
determine temperature $\Rightarrow$ energy density of medium

How to calculate quarkonium dissociation temperatures?

- determine heavy quark potential $V(r,T)$ in finite temperature QCD, solve Schrödinger equation
- calculate in-medium quarkonium spectrum $\sigma(\omega,T)$ directly in finite temperature lattice QCD

Consider static $Q\bar{Q}$ pair in QGP above T_c, at separation r

$\exists$ three interaction ranges, depending on $Q\bar{Q}$ separation distance



- $r_{J/\psi} \ll r_D(T)$: quarkonium does not see medium
- $r_{J/\psi} \gg r_D(T)$: Q does not see $\bar{Q}$
- $r_{J/\psi} \sim r_D(T)$: complex interactions

How to calculate $Q\bar{Q}$ potential?

- Heavy Quark Studies in Finite Temperature QCD

Hamiltonian $\mathcal{H}_Q$ for QGP with color singlet $Q\bar{Q}$ pair:

$$F_Q(r,T) = -T \ln \int d\Gamma \exp\{-\mathcal{H}_Q/T\}$$

Hamiltonian $\mathcal{H}_0$ for QGP without $Q\bar{Q}$ pair:

$$F_0(T) = -T \ln \int d\Gamma \exp\{-\mathcal{H}_0/T\}$$

study free energy difference $F(r,T) = F_Q(r,T) - F_0(T)$

internal energy difference $U(r,T)$ & entropy difference $S(r,T)$

$$U(r,T) = -T^2 \left(\frac{\partial [F(r,t)/T]}{\partial T} \right) = F(r,T) + TS(r,T)$$

relation to potential? $V = U$ or $V = F$ or mixture?

• weakly interacting plasma (QED, perturbative QCD)

Laine et al. 2007, Beraudo et al. 2008, Brambilla et al. 2008, Escobedo & Soto 2008, Burnier et al. 2009

real-time propagator of $Q\bar{Q}$ pair in medium $$V_w(r,T) = -\alpha\left[\mu(T) - \frac{1}{r}e^{-\mu(T)r}\right]$$

with $\mu(T) = 1/r_D(T) \sim \alpha T$

imaginary-time propagator of $Q\bar{Q}$ pair in medium $$F_w(r,T) = -\alpha\left[\mu(T) - \frac{1}{r}e^{-\mu(T)r}\right]$$

in perturbative limit, potential (real part) is free energy

entropy $$TS_w(r,T) = -\alpha\mu(T)\left[1 - e^{-\mu(T)r}\right]$$

internal energy $$U_w(r,T) = -\alpha\left[\mu(T) - \frac{1}{r}\right]e^{-\mu(T)r}$$

large distance limit (screening regime)

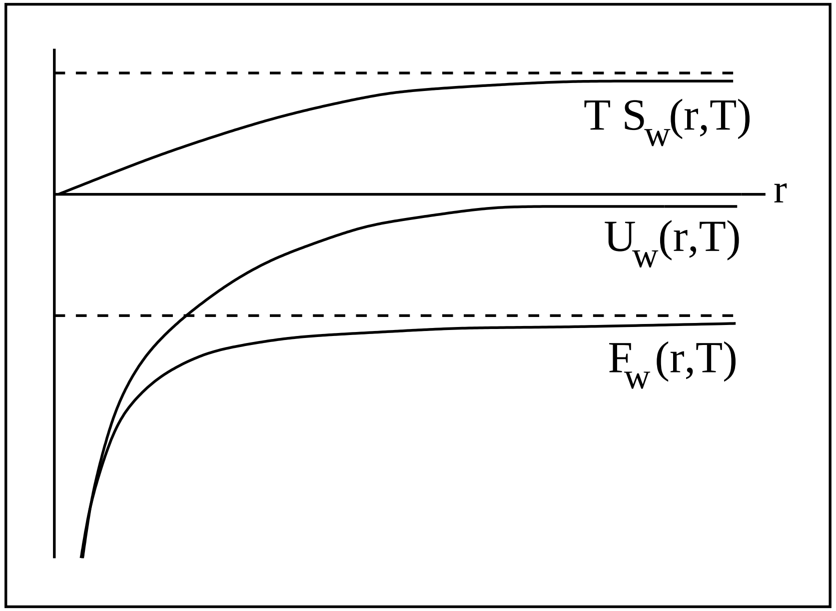
$$F_w(\infty, T) = -TS_w(\infty, T) = -\alpha\mu; \quad U_w(\infty, T) = 0$$

($\alpha\mu/2$ is “mass” of polarization cloud)

short distance limit (Coulomb regime)

$$F_w(r, T) = U_w(r, T) = -\frac{\alpha}{r}$$

$$TS_w(r, T) \rightarrow 0$$



melting process:

work done to separate $Q\bar{Q}$ is converted into entropy

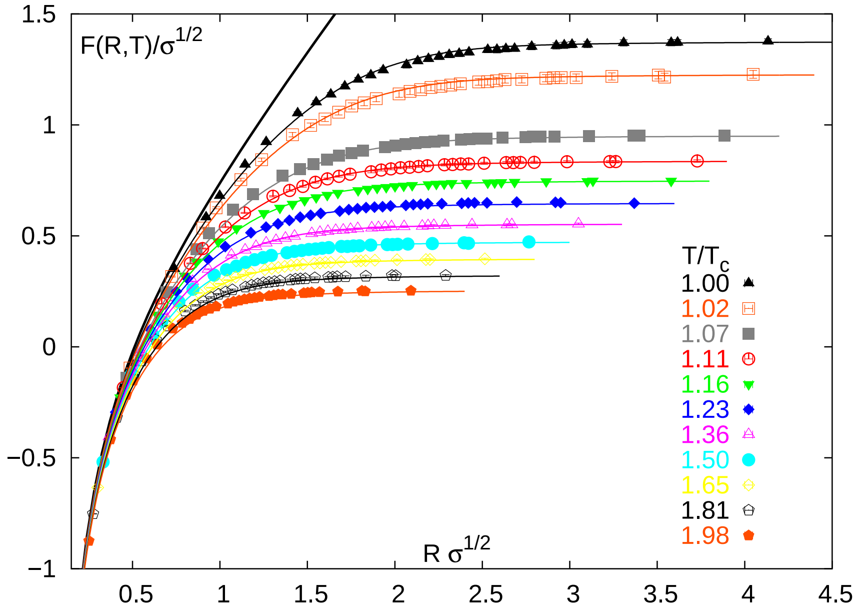
overall energy balance = 0

so far: perturbative limit $\sim$ weakly interacting plasma
(Debye-Hückel theory, slightly non-ideal gas)

QCD: very high $T \gg \Lambda_{\mathrm{QCD}}$ and/or very small $r \ll \Lambda_{\mathrm{QCD}}^{-1}$

• strongly interacting QGP ($T_c \leq T \leq 3\ T_c$)

Kaczmarek & Zantow 2005



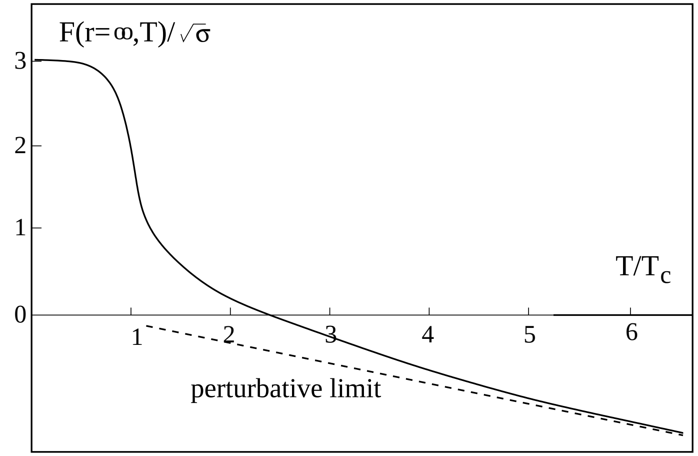
$\Rightarrow$ very different behavior
(lattice results, $N_f = 2$)

separate strong part

$$F(r,T) = F_w(r,T) + F_s(r,T)$$

$T_c \leq T \lesssim 3\,T_c$: strong deviations from perturbative limit

large distance limit



to parametrize lattice results

use 1-d Schwinger string form:

$$F_s(r,T) = \sigma r \left[\frac{1 - e^{-\mu(T)r}}{\mu(T)r}\right] = \frac{\sigma}{\mu(T)}\left[1 - e^{-\mu(T)r}\right]$$

large distance limit $F_s(\infty, T) = \sigma/\mu(T)$

in contrast to $F_w(\infty, T) = -\alpha\mu(T)$

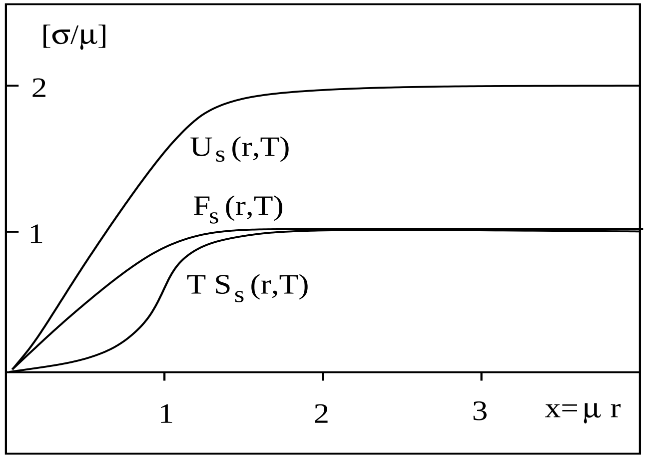
near T_c, $F_s \gg F_w$: $Q\bar{Q}$ in strongly interacting QGP?

two modifications:

- with $\mu(T) \sim T$, now obtain

$$T\,S_s(r,T) = \frac{\sigma}{\mu}\left[1-(1+\mu r)e^{-\mu r}\right]$$

$$U_s(r,T) = \frac{\sigma}{\mu}\left[2-(2+\mu r)e^{-\mu r}\right]$$



need one σ/μ to separate Q and $\bar{Q}$, and another σ/μ to form polarization clouds (entropy change)

Who pays for what?

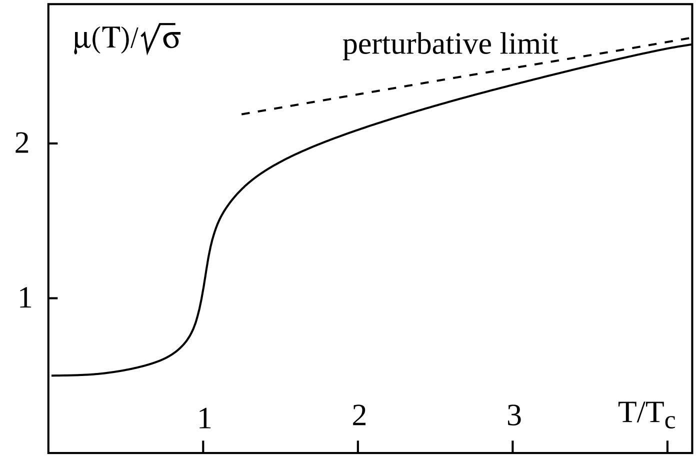
$V(r,T) = U(r,T)$ — the heavy quark pair pays all

$V(r,T) = F(r,T)$ — the medium pays the entropy change

$V(r,T) = xF(r,T) + (1-x)U(r,T)$ — medium and pair split the entropy cost the more the pair pays, the tighter is its binding....with obvious consequences on dissociation temperatures

- in the critical region $\mu(T) \not\sim T$, much stronger variation

  potential model calculations must use parametrization of lattice data



indicative results for $T_{\rm diss}/T_c$

state	$J/\psi(1S)$	$\chi_c(1P)$	$\psi'(2S)$
$V(r,T) = U(r,T)$	2.1	1.2	1.1
$V(r,T) = F(r,T)$	1.2	1.0	1.0

Digal et al. 2001; Shuryak & Zahed 2004; Wong 2004/5; Alberico et al. 2005; Digal et al. 2005; Mocsy & Petreczky 2005/6

• Lattice Studies of Quarkonium Spectrum

Calculate correlation function $G_i(\tau, T)$ for mesonic channel i determined by quarkonium spectrum $\sigma_i(\omega, T)$

$$G_i(\tau, T) = \int d\omega \ \sigma_i(\omega, T) \ K(\omega, \tau, T)$$

relates imaginary time τ and $c\bar{c}$ energy ω through kernel

$$K(\omega, \tau, T) = \frac{\cosh[\omega(\tau - (1/2T))]}{\sinh(\omega/2T)}$$

invert $G_i(\tau, T)$ to get quarkonium spectra $\sigma_i(\omega, T)$

Basic Problem

correlator given at discrete number $N_\tau/2$ of lattice points with limited precision; presently best $N_\tau = 96 \ (0.75 \ T_c), \ 48 \ (1.5 \ T_c)$

want spectra $\sigma_i(\omega, T)$ at ~ 1000 points in ω

• brute force solution: calculate correlators for $N_\tau = 2000$
then inversion is well-defined – project for FAR distant future

• in the meantime: invert $G(\tau, T)$ by MEM to get $\sigma(\omega, T)$

Maximum Entropy Method (MEM)   here: Asakawa and Hatsuda 2004

what is the most likely solution for given data, given errors and some basic information?

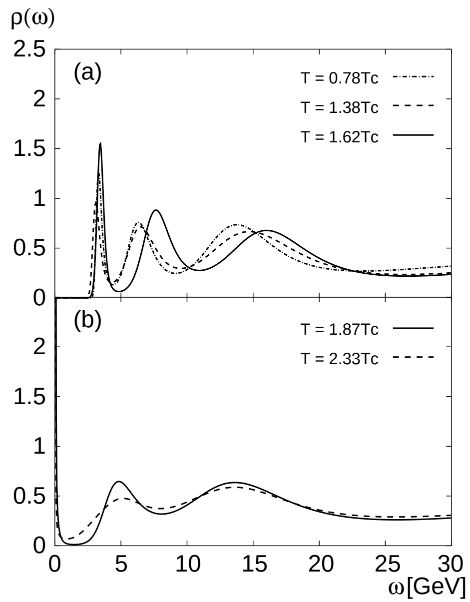
charmonia quenched:

Umeda et al. 2001
Asakawa & Hatsuda 2004
Datta et al. 2004
Iida et al. 2005
Jakovac et al. 2005

charmonia unquenched:

Aarts et al. 2005, 2007

first results $\Longrightarrow$



- MEM requires input reference ("default") function for σ;
  form of and dependence on default function?

Preliminary work: Heng-Tong Ding, O. Kaczmarek, F. Karsch, HS

choose two extreme cases as DF

– DF1: $\sigma(\omega, T = 0)$, quarkonium spectrum in vacuum

– DF2: $\sigma_{\text{free}}(\omega, T)$, spectrum for free $Q\bar{Q}$ pair at T

- what does MEM specify for $\sigma(\omega, T)$ from correlators at T?

- consider calculations in quenched QCD for PS channel

– at $T = 0.75\ T_c$ for $N_x = 128,\ N_\tau = 96$, 132 configs.

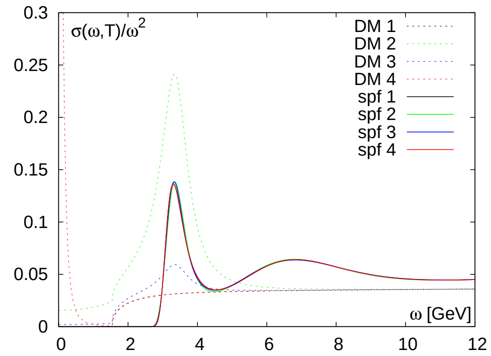
– at $T = 1.50\ T_c$ for $N_x = 128,\ N_\tau = 48$, 471 configs.

– at $T = 2.25\ T_c$ for $N_x = 128,\ N_\tau = 36$, xxx configs.

– at $T = 3.00\ T_c$ for $N_x = 128,\ N_\tau = 24$, xxx configs.

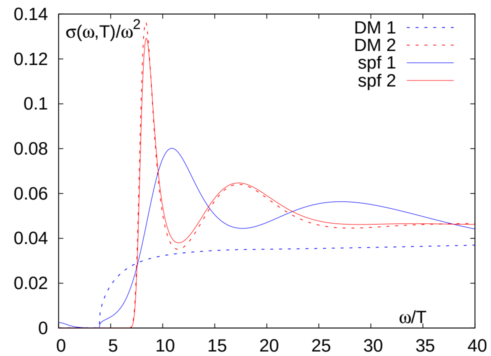
information sufficient
for unique MEM results;
spatial lattice size
insufficient for resonance width

$T = 0.75\ T_c$



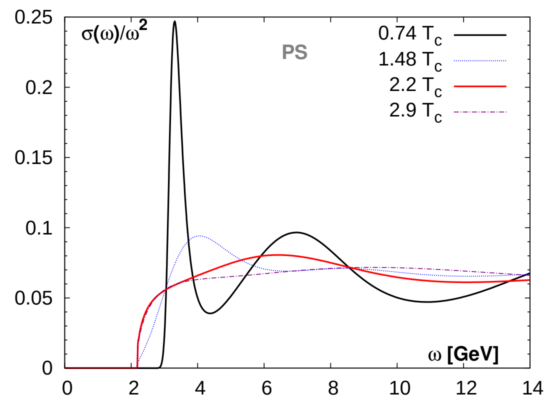
information insufficient
for unique MEM results;
spatial lattice size
insufficient for resonance width

$T = 1.50\ T_c$

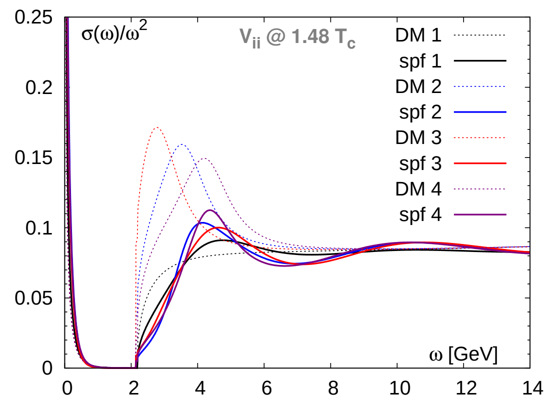


- better statistics, larger N_τ should resolve MEM results
- larger N_x should (eventually) resolve resonance width

Some further results:



increasing T shifts "peak"
to higher mass:
$\Rightarrow$ thermal peak of
unbound heavy quarks



change of default peak
not accepted by MEM

Tentative summary so far:

- J/ψ survives up to $T \simeq 1.5 - 2.0\ T_c$
- χ and ψ' dissociated at or slightly above T_c

But there are further questions:

– **Schrödinger equation provides dissociation temperature as point where J/ψ radius diverges, binding energy vanishes;**

$R \simeq 5$ fm, $\Delta E \simeq 10$ MeV in medium of $T \simeq 250$ MeV?

– **Lattice calculations provide quarkonium spectrum with given resonance width, position;**

how wide can it get, how far can it shift and still be J/ψ?

Possible way out: melting region is quite narrow in T?

$\exists$ observable consequences for nuclear collision experiments?

3. Quarkonium production is suppressed in nuclear collisions

...but for a variety of reasons

- nuclear modification ("shadowing") of parton distribution functions
- parton energy loss in cold nuclear matter
- pre-resonance dissociation ("absorption") in cold nuclear matter
- dissociation by screening ("melting") and/or collisions in hot QGP

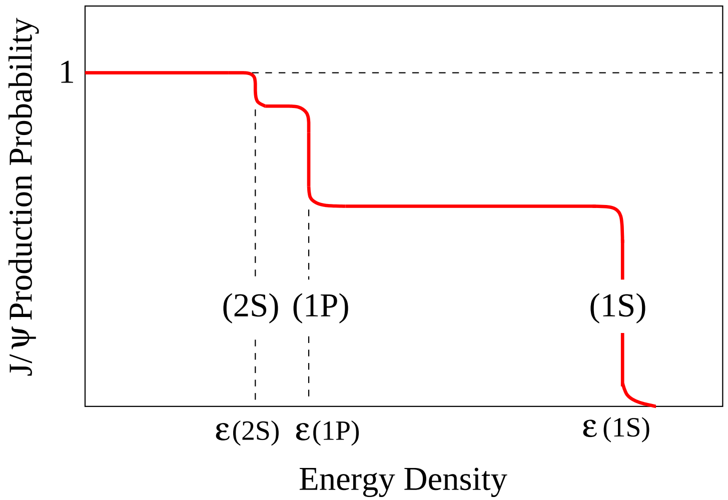
assume both initial & final state cold nuclear matter effects are taken into account correctly;

SPS & RHIC: $\exists$ remaining 50 % $\pm$? "anomalous" suppression

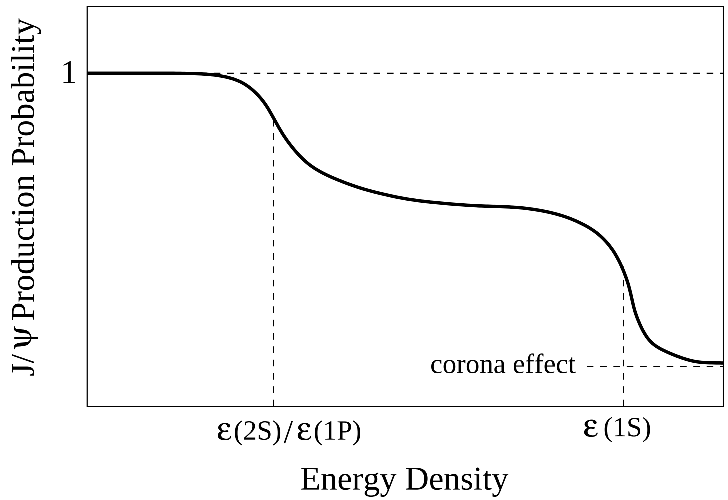
If due to melting in hot QGP $\Rightarrow$ sequential J/ψ suppression

Karsch & HS 1991; Gupta & HS 1992; Karsch, Kharzeev & HS 2006

- measured J/ψ's are about 60% direct 1S, 30% χ_c decay, 10% ψ' decay
- narrow excited states $\longrightarrow$ decay outside medium; medium affects excited states
- J/ψ survival rate shows sequential reduction: first due to ψ' and χ_c melting, then later direct J/ψ dissociation
- experimental smearing of steps; corona effect



$\Rightarrow$



IF charmonium/bottomonium thresholds are measurable:

- experimental test of quantitative statistical QCD results

⇒ no charmonium production at the LHC?

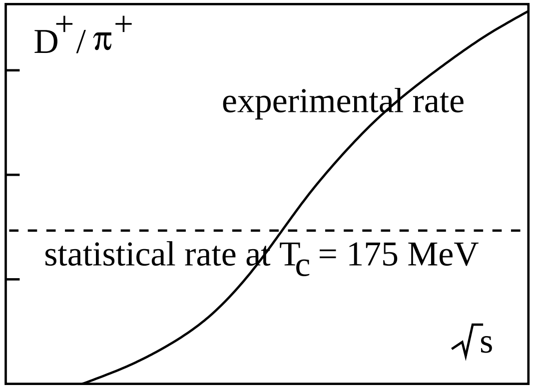
– corona effect

– significant B production → charmonium production via feed-down from B decay; check through pp studies. And:

4. Quarkonia can be created at QGP hadronization

Braun-Munzinger & Stachel 2001, Thews et al. 2001, Grandchamp & Rapp 2002
Andronic et al. 2003, Zhuang et al. 2006

- $c\bar{c}$ production is dynamical "hard process":
  at high energy, produced medium contains more than the "statistical" number of charm quarks



- **assume**
  - **charm quark abundance constant in evolution to T_c**
  - **charm quarks form part of equilibrium QGP at T_c**
  - **equilibrium QGP at T_c hadronizes statistically**
  - **charmonium production via statistical $c\bar{c}$ fusion**
- **"secondary" charmonium production by fusion of c and $\bar{c}$ produced in different primary collisions**
- **insignificant at "low" energy, since very few charm quarks; could be dominant production mechanism at high energy**

- **simplified illustration...assume at "LHC" per event**

$$100 \; c\bar{c} \text{ pairs} \qquad\qquad 1000 \; q\bar{q} \text{ pairs}$$

non-statistical fraction; statistical $\sim 10^{-3}$ **for** $T_c = 175$ **MeV**

primary rates:

$$1 \; J/\psi,\; 99 \; D,\; 99 \; \bar{D},\; 901 \text{ light hadrons} \Rightarrow \; R_{AA} \simeq 1$$

rates for statistical combination of given quark abundances:

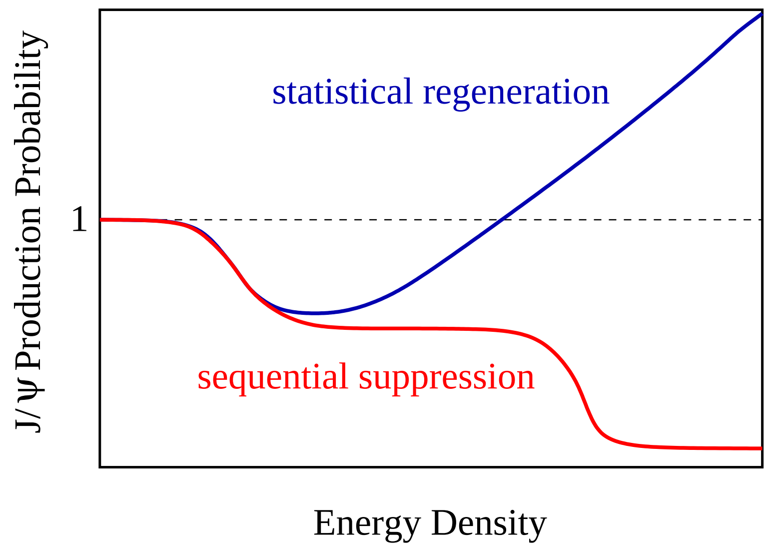
$$10 \; J/\psi,\; 90 \; D,\; 90 \; \bar{D},\; 910 \text{ light hadrons} \;\Rightarrow\; R_{AA} \simeq 10$$

$\Rightarrow J/\psi$ **production strongly** <u>**enhanced**</u> **re scaled** pp **rate**

$$\Rightarrow \frac{J/\psi}{D} \simeq 0.1 \text{ instead of } 0.01 \text{ in } pp$$

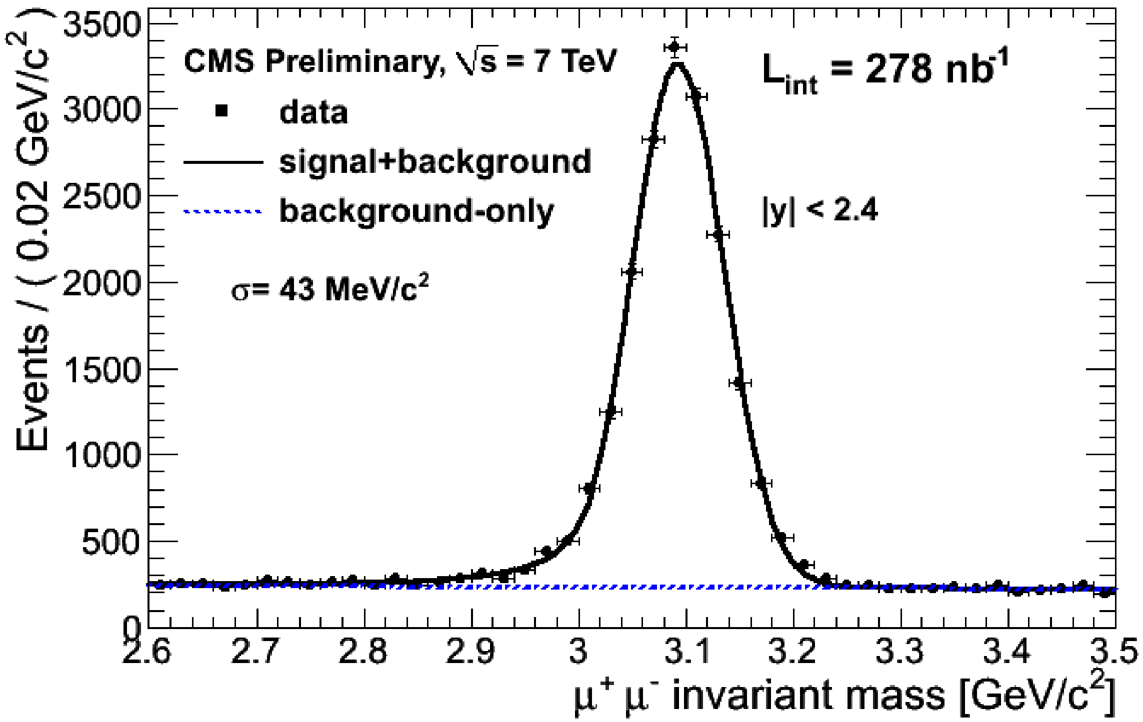
ratio of hidden/open charm strongly enhanced re pp ratio

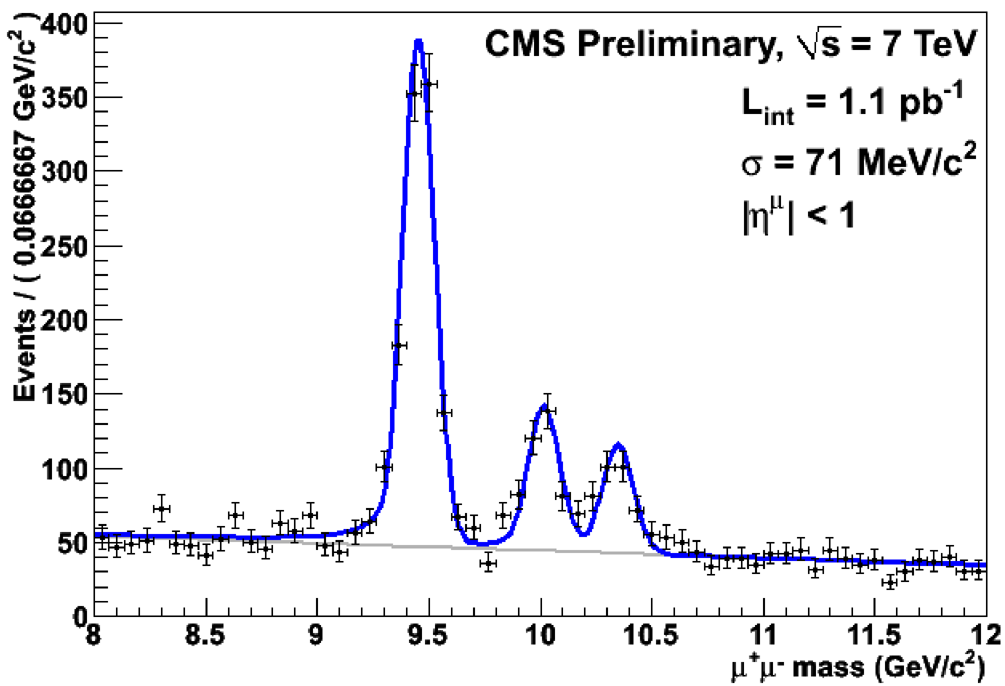
two readily distinguishable predictions for anomalous J/ψ production

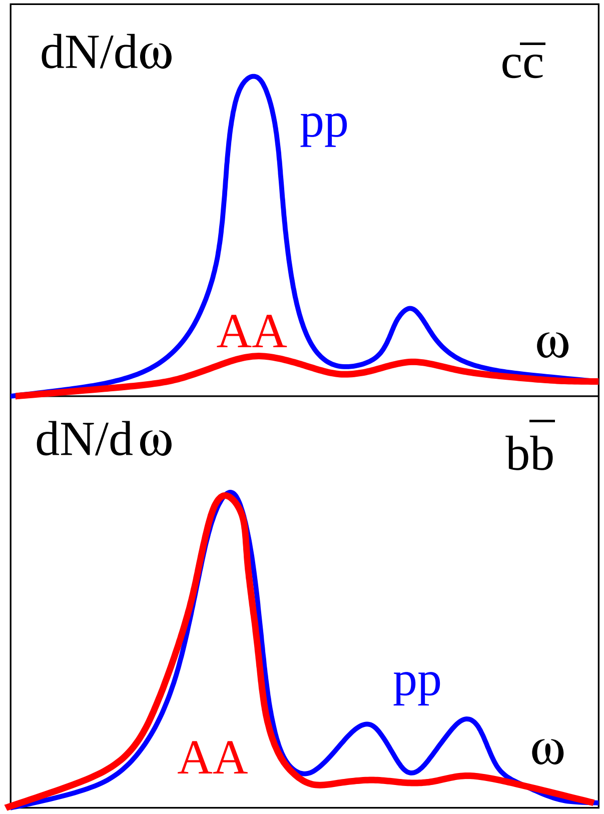


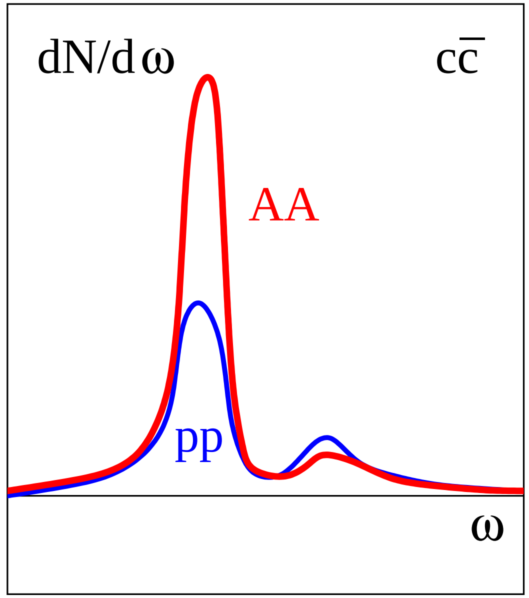
dynamical vs. statistical momentum spectra Mangano & Thews 2003

NB: assumption of statistical quarkonium binding...


CMS Preliminary, $\sqrt{s}$ = 7 TeV
data
signal+background
background-only
σ= 43 MeV/c^2
L_{int} = 278 nb^{-1}
|y| < 2.4
Events / (0.02 GeV/c^2)
0
500
1000
1500
2000
2500
3000
3500
2.6
2.7
2.8
2.9
3
3.1
3.2
3.3
3.4
3.5
$\mu^+ \mu^-$ invariant mass [GeV/c^2]


CMS Preliminary, $\sqrt{s}$ = 7 TeV
L_{int} = 1.1 pb^{-1}
σ = 71 MeV/c^2
$|\eta^{\mu}| < 1$
Events / (0.0666667 GeV/c^2)
$\mu^+\mu^-$ mass (GeV/c^2)





sequential suppression by color screening: only (possible) survivor is Υ

statistical regeneration: more J/ψ than in scaled pp

Conclusions

Given reference measurements of open charm/bottom production,

experimental quarkonium studies at the LHC can ask

conceptual [model-independent] questions and provide

conceptual [model-independent] answers to these.

Quantitative details require specific theory/model input.